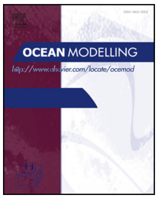
Ocean Modelling 129 (2018) 13–38

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod



Finite-Element barotropic model for the Indian and Western Pacific Oceans: Tidal model-data comparisons and sensitivities

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ARTICLE INFO

Keywords:
Finite-element
Unstructured grid
Barotropic tides
Bathymetry
Internal tide energy conversion
Bottom friction

ABSTRACT

In this study, a 9.6 million node large-scale unstructured grid finite-element forward barotropic model is developed and applied to understand the tidal dynamics and dissipation mechanisms of the Indian and western Pacific Oceans down to sub-kilometer scale at the coast. Tidal model-data comparisons are presented to assess the capabilities and limitations of our large-scale barotropic model. The average root-mean-square (RMS) discrepancies of tidal elevations at coastal tide gauges is 14 cm, which is ~ 3 cm smaller than those of a state-of-the-art global data assimilated barotropic tidal model. Sensitivities to lateral boundary conditions, bathymetry, and dissipative processes are explored to guide future endeavors related to large-scale barotropic modeling in the region and other regions throughout the world. Lateral boundary conditions are found to induce adverse resonant effects on the lunar semi-diurnal modes when poorly placed elevation specified boundary conditions are used. This problem is largely resolved by using an absorption-generation layer at the boundary. Parameterization of internal tide energy conversion is identified as the most important aspect to control deep water solutions, and help reduce the RMS discrepancies of the entire system. Two forms of this parameterization are presented and their spatial distributions of dissipation are compared. Bathymetry has a negligible effect on the tidal solutions in deep water, but local high resolution bathymetry results in significant reductions to the average RMS discrepancies on the continental shelf (26%) and at the coast (30%). Implementing a spatially varying bottom friction coefficient based on sediment types decreases the average RMS discrepancy at the coast by 9% predominantly due to its positive effects in the Yellow Sea. The model is shown to capture a large amount of the tidal physics and has the potential for application to a range of barotropic problems such as wind-driven surge and tidal processes.

1. Introduction

The Indian and western Pacific Oceans represent approximately 30% of the surface area of the world oceans. They are interconnected by marginal seas such as the Java, Timor, Banda, Andaman and Arafura Seas, and are separated by the intricate island chains of Indonesia and the Philippines. Major ports and cities are located in the northern parts of both the Indian Ocean (Dubai, Karachi, Mumbai, Colombo) and the western Pacific Ocean (Hong Kong, Shanghai, Tokyo, Singapore), representing a significant portion of the world's economy and human population. Thus, within this region (which we call *IndWPac* hereafter), there is great interest in being able to better understand coastal hazards and hydrodynamics for e.g., coastal protection and management, risk evaluation, and navigational purposes.

For such purposes, our long-term objective is to develop a large domain depth-integrated forward model of the IndWPac region which couples tides, atmospheric driven currents, density driven circulation, and wind waves. The focus is to advance the modeling of these individual processes and systematically understand the interactivity of dissipation mechanisms, bathymetric sensitivities, and lateral boundary forcing mechanisms on the response functions throughout this domain. In particular, our interests lie on inner shelf and estuarine processes, and how these mechanisms impact coastal and inland water levels and currents. This is notwithstanding the challenge of the IndWPac region in terms of its complex geometry, topography (such as the many interconnected shallow seas and island chains), and associated

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https://doi.org/10.1016/j.ocemod.2018.07.003
Received 31 January 2018; Received in revised form 4 July 2018; Accepted 16 July 2018

hydrodynamics in comparison with e.g., the western North Atlantic region that has received significant attention (Hope et al., 2013; Kerr et al., 2013; Bunya et al., 2010).

To model the dynamics at coastal and inland locations within the IndWPac region, all processes and exchanges from ocean scale to harbor inlet scale, must be appropriately represented. Coarse resolution global models (e.g. Egbert et al., 2004; Green and Nycander, 2013; Buijsman et al., 2015; Green et al., 2017) have been developed to simulate the large-scale global ocean dynamics, but as a result of grid resolution they may inadequately capture geometric features and nonlinearities of the hydrodynamics in the inner shelf and nearshore region. Conversely, higher resolution shelf scale regional domain models are often developed to accurately capture local effects (e.g. Green and David, 2013; Cai et al., 2006; Zu et al., 2008, in South China Sea). However, accurate lateral boundary conditions are required to propagate in all of the required information from offshore. The closer one gets to the coast, the more boundary conditions become complicated and difficult to match with the interior domain physics in order to correctly exchange mass, momentum and energy across the boundary. Furthermore, regional model parameters are calibrated to generate accurate results in the specific region that may not be generally applicable in other regions.

Thus, this study presents the development of an ocean basin scale model which minimizes lateral boundary interaction, yet sufficiently resolves energetic processes from the deep water to the coast using a single unstructured computational grid in a physically consistent manner without ad-hoc parameterization. The scale of this model fits somewhere in between the global scale and shelf scale regional models that are more commonly developed. The ocean basin scale model utilizes varying resolutions to produce high fidelity coastal bathymetry of critical geographic and topographic features such as island chains, reef systems, and floodplain systems; provides connectivity to estuarine and harbor systems where dense coastal populations live; and captures key dynamics of a large regional domain in which the effects of changing dynamics in a certain region can propagate into other regions. At the same time, lateral boundaries are placed further offshore than shelf scale regional models, thus more focus is placed on the inner model dynamics allowing the governing physics to equilibrate without constraining the system. Hence, a more accurate understanding of the controls and the extent of impact throughout the domain may be obtained. Note that in future work as computational resources allow, we would like to extend this ocean basin scale model to the global scale while maintaining high resolution in the coastal areas.

The aim is to systematically build complexity into the external forcing terms and the underlying physics. In the process, sensitivity of the dynamical system and sub-grid scale parameterizations will be explored to assess the capabilities and limitations of the model in the IndWPac region. In this study, we begin this process through model-data comparisons of tidal elevations (predominantly) and tidal currents due to astronomical forcing. Since tides can be reduced to a series of harmonic constituents of well-defined frequencies, model-data comparisons can be robustly made. Comparisons are conducted against point observations at tide gauges and regionally against global data-assimilative model atlases. Examples of the latter include TPXO8 (Egbert and Erofeeva, 2002) (http://volkov.oce.orst.edu/tides/tpxo8_atlas.html), FES2014 (Lyard et al., 2006) (https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes/description-fes2014.html), and NAO.99b (Matsumoto et al., 2000). These models assimilate elevation data from satellite altimetry and selected coastal tide gauges to accurately obtain estimates of the tidal elevation fields in terms of individual harmonic constituents. M_2 tidal wave root-mean-square errors (RMSE) of modern data assimilated models are typically 0.5-0.7 cm versus deep-ocean bottom pressure recorder stations (Stammer et al., 2014). In contrast, M_2 RMSE ranges within 5.6-12.7 cm for purely hydrodynamic global models without data-assimilation (Stammer et al., 2014). However, non-assimilative forward models on large domains can be applied to a wide variety of problems including wind, pressure, ice and wave coupling effects, and may be used to conduct past (Egbert et al., 2004; Green, 2010; Wilmes and Green, 2014; Green et al., 2017) or future forecasting and perturbation response analysis (Green and David, 2013), e.g., due to changing sea level, large-scale ice sheet collapse (Wilmes et al., 2017), dredging operations, and land reclamation (Suh et al., 2014).

Importantly, this study explores the sensitivities of various controls on the barotropic tidal dynamics. At first, the effects of lateral boundary placement, and the addition of an absorption-generation sponge layer at the lateral boundary, are discussed. Secondly, the responses to two different global bathymetric databases are directly compared. Thirdly, high resolution local bathymetric data are included, where available, to assess its potential to facilitate improvements in the solution. Lastly, internal tide and bed stress (bottom friction) driven dissipative effects are explored: After it was discovered that around 25-30% of the total global tidal dissipation is in the deep ocean (Egbert and Ray, 2000), the conversion of barotropic energy into baroclinic energy through the generation of internal tides over rough submarine topography was determined to be an important process to include in ocean tide models (for a review see Garrett and Kunze, 2007). Parameterizations of *internal tide energy conversion* (in which it is incorporated as a sink term) through this process is critical to reduce tidal elevation discrepancies in barotropic ocean models (Jayne and St. Laurent, 2001; Egbert et al., 2004; Zaron and Egbert, 2006; Green and Nycander, 2013; Buijsman et al., 2015). The effects of the energy conversion parameterization in the IndWPac region, including comparisons between two different forms of parameterization, are discussed. In addition, spatially varying bottom friction coefficients in the parameterization of bed stress are rarely considered in large-scale models. Instead, a canonical spatially constant coefficient is commonly applied (Lyard et al., 2006; Egbert and Erofeeva, 2002). However, changing the bottom friction coefficient has been shown to have positive effects regionally (Kerr et al., 2013; Lefevre et al., 2000). We briefly discuss the impacts of estimating spatially varying coefficients based on local sediment types and the local hydrodynamics. The requirements for improved estimations of local bottom friction coefficients for future research are considered.

To summarize, this paper describes the development of the IndWPac unstructured grid and hydrodynamic modeling system (§2-3). It is built with state-of-the-art bathymetric datasets (§2), absorption-generation boundary conditions (§3.5), and data-informed parameterizations of internal tide energy conversion (§3.3) and bottom friction dissipation (§3.4). We analyze the sensitivity of the model to these four factors (§5), and conduct model-data comparisons of tidal elevations and tidal currents against both tide gauge records and a data assimilated tidal model (§4). The capabilities and limitations of the model are identified and discussed (§4-5). Suggested areas of focus to advance barotropic coastal ocean models are highlighted.

2. Domain definition, bathymetry, and unstructured grid development

Our ocean basin scale model includes the entire Indian Ocean, the western half of the Pacific Ocean, and the Southern Ocean between these extents. Specifically, the domain (Fig. 1) lies between 17.9°E - 175.8°E longitude and 73.3°S - 62.7°N latitude covering an area of roughly 150 million km^2. There are two open ocean boundaries: a longitudinal parallel boundary running from nearby the Cape of Good Hope, South Africa to Antarctica; and a concave shaped boundary between the Bering Sea coast of Kamchatka Krai, Russia and Antarctica. The boundaries were chosen so that tidal amphidromic points and complications with the Aleutian, Hawaiian and New Zealand islands in the Pacific Ocean were avoided (an illustration on the effects of boundary placement is shown in §5.1).

The mesh is a triangular unstructured grid with resolution ranging from as large as 25 km in parts of the deep ocean down to 1 km along most coastlines (Fig. 1(b)). Additionally, resolution is as fine as 100 m